#10 J. Douglas 1/16/04

SUBSTITUTE SPECIFICATION

a

METHOD FOR ATSC DTV MULTIPATH EQUALIZATION AND ASSOCIATED DEVICES

Related Application

[0001] The present application is based upon copending provisional patent application no. 60/201,537 filed April 24, 2000, the entire contents of which are incorporated herein by reference.

Field of the Invention

[0002] The present invention relates to digital television (DTV), and in particular, to the advanced television systems committee (ATSC) standard for terrestrial broadcast television in the United States.

Background of the Invention

[0003] The ATSC DTV standard was determined by the "Grand Alliance" and was subsequently accepted by the broadcast community, the consumer electronics industry and the regulatory infrastructure. The regulatory infrastructure has mandated a strict schedule for the transition of terrestrial broadcast television in the United States from the national television system committee (NTSC) to the ATSC standard. The NTSC standard is an analog standard whereas the ATSC is a digital standard. A significant investment is in place, on behalf of the broadcast industry, to support this planned transition. Similarly, many consumers have purchased ATSC television receiver equipment in

the form of new ATSC-system compliant DTV television sets and in the form of DTV television set-top converters.

[0004] However, the ATSC standard, in its present form, is deficient in its susceptibility to multipath. In a side-by-side comparison, reception of the new digital system ATSC standard is often inferior to reception of the conventional analog system NTSC standard. Additionally, ATSC mobile reception suffers a more substantial degradation due to multipath than NTSC mobile reception. It is also well known that signal strength and signal-to-noise ratios (SNR) are not at issue. Unanticipated inferior reception manifests itself at high levels of received signal power and at high receiver signal-to-noise ratios. This fact, coupled with spectral analysis of received ATSC DTV signals, points directly to multipath as the cause of inferior reception.

[0005] Significant work in the area of DTV reception is available. For example, U.S. Patent No. 5,592,235 to Park et al. describes terrestrial broadcast reception and cable broadcast reception in a single receiver. U.S. Patent No. 5,802,241 to Oshima describes a plurality of modulation components modulated by a plurality of signal components.

[0006] Decision-feedback equalizers (DFE) have been used in digital demodulation. Unfortunately, decision-feedback equalization is not suitable for enabling the initial acquisition of digital modulation severely distorted by multipath-induced intersymbol interference. For this purpose, a reference waveform or reference sequence is typically introduced. The use of a reference sequence equalizer is disclosed in U.S.

Patent No. 5,886,748 to Lee, which describes in very general terms the use of a reference sequence for equalizing GA-HDTV signals. However, Lee does not address the multipath issues relevant to ATSC DTV reception. In addition, Lee does not address the compatibility between the referenced training sequence with the existing ATSC DTV standard, and does not address the relevance or appropriateness of the referenced training sequence and equalization method to VHF and UHF multipath.

[0007] Also of interest to terrestrial ATSC DTV in the United States is U.S. Patent No. 5,923,378 to Limberg. Limberg addresses NTSC to DTV interference issues relevant to the DTV transition plan in effect in the United States. Also of interest is U.S. Patent No. 5,943,372 to Gans et al., which discloses the combination of diversity transmission with complementary forward error correction. Unfortunately, none of these prior art references provide an effective remedy for multipath with respect to the ATSC DTV standard for terrestrial broadcast DTV.

Summary of the Invention

[0008] In view of the foregoing background, an object of the present invention is to reduce the susceptibility of the ATSC DTV standard to multipath for terrestrial broadcast DTV.

[0009] This and other objects, advantages and features in accordance with the present invention are provided by a method that enables a reference or training sequence or waveform equalization by introducing an equalizer training waveform compatible

with the present ATSC DTV standard for terrestrial broadcast DTV in the United States.

[00010] A training waveform is introduced into the ATSC DTV modulation waveform by introducing training sequence placeholders onto the ATSC DTV multiplex and transport. Subsequent processing yields modulation training suitable for allowing the adaptive equalization processes required at the receiver to address VHF and UHF multipath. The necessary transmission signal processing is accomplished with no hostile effects in terms of backward compatibility with pre-existing legacy ATSC DTV receivers. The training waveform is introduced specifically to enable training-waveform-based equalization that is adequate and necessary to address multipath induced intersymbol interference otherwise known to be catastrophic to ATSC DTV reception.

[00011] ATSC DTV modulation is preserved and ATSC DTV multiplex and transport remain compatible with the existing ATSC DTV standard. As such, the existing ATSC DTV infrastructure is compatible with the disclosed ATSC DTV multipath approach. Existing ATSC DTV receivers continue to function as they have functioned before.

[00012] Retrofit of pre-existing consumer ATSC DTV receiver equipment is unnecessary. However, the production of new consumer ATSC DTV receiver equipment is made possible, through this disclosure, with minimum economic disruption. The practical cost and complexity of the necessary transmission equipment upgrade is reduced through the backwards-compatible ATSC DTV multiplex and transport training sequence induction technique disclosed herein. In addition, a substantial

and significant advantage with respect to multipath equalization processing is also obtained.

Brief Description of the Drawings

[00013] FIG. 1 is a general block diagram of an ATSC DTV transmission system in accordance with the prior art.

[00014] FIG. 2 illustrates an ATSC DTV modulation frame for the ATSC DTV transmission system shown in FIG. 1.

[00015] FIG. 3 is a conceptual illustration of multipath in accordance with the prior art.

[00016] FIG. 4 is a block diagram of a continuous-time modulator and channel model in accordance with the prior art.

[00017] FIG. 5 is a block diagram of an equivalent time-sampled modulator and channel model in accordance with the prior art.

[00018] FIG. 6 is a block diagram of an adaptive blind equalizer in accordance with the prior art.

[00019] FIG. 7 is a block diagram of an adaptive decision-feedback equalizer in accordance with the prior art.

[00020] FIG. 8 is a block diagram of an adaptive training waveform equalizer in accordance with the prior art.

[00021] FIG. 9 is a simplified block diagram of ATSC DTV transmission and reception systems in accordance with the prior art.

[00022] FIG. 10 is a simplified block diagram of ATSC DTV transmission and reception systems retrofitted for standard noncompliant training waveforms in accordance with the prior art.

[00023] FIG. 11 is a simplified block diagram of ATSC DTV transmission and reception systems retrofitted for backwards-compatible induced equalizer training symbols in accordance with the present invention.

[00024] FIG. 12 is a general block diagram of the ATSC DTV transmission system highlighting the data interleaving process in the presence of training sequence induction data in accordance with the present invention.

[00025] FIG. 13 illustrates the introduction of induction packet sequences at a rate of 1 induction packet per 13 ATSC DTV multiplex packets in accordance with the present invention.

[00026] FIG. 14 illustrates the ATSC DTV byte interleave process in accordance with the present invention.

[00027] FIG. 15 illustrates an example where an interleaved frame has been formed by introducing 1 induction packet per 6 ATSC DTV multiplex packets in accordance with the present invention.

[00028] FIG. 16 illustrates the ATSC DTV TCM byte interleave process in accordance with the present invention.

[00029] FIG. 17 illustrates the ATSC DTV TCM bit interleave process in accordance with the present invention.

[00030] FIG. 18 illustrates the ATSC DTV TCM encode process in accordance with the present invention.

Detailed Description of the Preferred Embodiments

[00031] The ATSC DTV transmission system is illustrated in FIG. 1. The transmission system includes a multiplexer **125** for multiplexing various

components of the broadcast program, including video **105**, audio **110**, data **115** and control information **120**. The service multiplex stream **130** is randomized by a randomizer **135**, Reed-Solomon encoded by an RS encoder **140**, byte-interleaved by a data interleave circuit **145** and TCM encoded by a Trellis encoder **150** in preparation for modulation. Modulation includes introducing a segment sync **155** and a field sync **160** to a multiplexer **165**, then adding a pilot signal at a pilot insert circuit **170**, followed by pre-equalization by a pre-equalization filter **175**, VSB modulation by a VSB modulator **180** and RF up-conversion by a converter **185**. The modulation format is commonly described in terms of the ATSC DTV modulation frame as best illustrated in FIG. 2.

[00032] The foremost weakness of the ATSC DTV standard for terrestrial broadcast digital television is its susceptibility to multipath. FIG. 3 illustrates the dilemma caused by multipath. The propagation path from the broadcast transmitter site **310** to any given receiver site (an NTSC site **380** or a DTV site **390**) may involve any whole number of propagation paths **320, 330, 340, 350, 360** and **370**. Each propagation path **320, 330, 340, 350, 360** and **370** has an independent or unique amplitude, as well as delay and phase characteristics.

[00033] A customary consumer antenna does not distinguish from multiple paths. Such a process (multiple antennas or phased array antennas) is beyond the capability of conventional consumer electronic equipment used in television reception. Consequently, each received signal from each of the propagation paths **320, 330, 340, 350, 360** and **370** contributes either constructively or destructively with respect to the

other received signals. It is more likely that two or more propagation paths **320, 330, 340, 350, 360** and **370** add destructively rather than constructively. The complication of multiple additive amplitudes, phases and delay responses yields a received signal subject to unpredictable linear time and frequency distortion, i.e., self-interference.

[00034] Still referring to FIG. 3, an NTSC (conventional analog) receiver **380** is shown above a DTV (ATSC standard digital) receiver **390**. This aspect of FIG. 3 serves to illustrate the present dilemma faced by the broadcast industry. In the case of the conventional analog NTSC system **380**, multipath manifests itself in terms of analog interference. The resulting program distortion manifests itself primarily as ghosting. Ghosts of the analog image includes superimposed copies of the picture appearing over the intended picture in the video display. Ghosts are commonly observed in terrestrially received NTSC video images. Video image ghosting is sometimes tolerable to the viewer, as ghosting may or may not be substantially significant in terms of image degradation. This is in contrast to the multipath distortion effects commonly observed in the reception of digital signals from an ATSC system **390**.

[00035] With respect to the ATSC modulation waveform, multipath manifests itself in intersymbol interference. Intersymbol interference is known in ATSC systems to cause catastrophic failures. There is no ghosting or graceful degradation. The signal is simply lost (SNR cliff effect) or it is never acquired (when intersymbol interference violates demodulation signal acquisition thresholds). In the former case, the visible result is

image freezing or deresolution due to the loss of data. The audible result is muted (loss of audio). In the latter case, the visible result is a blank screen and silent audio. Based on these observations, and on their corresponding frequency of occurrence, one skilled in the art of television reception arrives at the conclusion that the ATSC DTV standard format, in its present form, presents a service degradation with respect to reception reliability.

[00036] Multipath may be modeled in continuous time as a linear convolutional process $h(t,\tau)$ **440** as shown in FIG. 4. In this figure, the symbol sequence $x(n)$ **410** is applied to the modulator **420** for producing a modulation waveform $s(t)$ **430**. The propagation channel is represented by the convolutional process $h(t,\tau)$ **440** and the additive **470** noise process $n(t)$ **460**. The resulting signal $r(t)$ **480** is received at the ATSC DTV receiver.

[00037] The modulation and channel propagation processes lend themselves to a time-sampled representation as shown in FIG. 5. In this figure, the modulation signal $s(n)$ **530** is modeled as a time-sampled waveform in time index n. Although the same time index is used for the symbol sequence $x(n)$ **410**, it is important to note that N x sampling (i.e., N-times sampling) is common to digital signal processing with respect to both transmission and reception systems. The use of the same time index for both waveforms is not intended to preclude the use of N × sampling. The modulation symbol sequence $x(n)$ **410** in time index n is to be thought of as adhering to the identical N ×

sampling process and includes repeated sets of N-1 zero samples interspersed with single symbol states.

[00038] In addition, the absence of complex notation throughout this application should not be misconstrued as to preclude the use of complex sampling. Complex sampling is both anticipated and expected, and is omitted in this application merely for the sake of simplifying the disclosure.

[00039] In FIG. 5, the same linear convolutional multipath response $h(t,\tau)$ **440** is modeled as a time-sampled vector process $\overline{h}(n,m)$ **540** where n is the time index and m is the time-response index, indicating a vector sampled-time response in m at every time sample n. Lastly, channel noise $n(n)$ **560** is added **570** on a sample-by-sample basis to yield the received time-sampled waveform $r(n)$ **580**.

[00040] This time-sampled model is applied to the drawings, which illustrate the prior art as applied to ATSC DTV equalization. FIG. 6 illustrates a blind equalizer used to adaptively converge on a sufficiently accurate approximation $\hat{\overline{h^{-1}}}(n,m)$ **610** of the inverse $\overline{h^{-1}}(n,m)$ of the channel response $\overline{h}(n,m)$ **540** using an adaptive algorithm **650**. FIG. 7 illustrates the decision feedback equalizer applied for the same purpose. A training waveform equalizer is illustrated in FIG. 8. In all cases, the prior art has failed to produce a suitable equalizer and/or demodulator for reliably receiving the conventional ATSC DTV terrestrial broadcast waveform in the presence of significant multipath.

[00041] An inherent weakness of the ATSC DTV standard system, as illustrated in the simplified block diagram of FIG. 9, is the 24.2 ms interval **220** (as illustrated in FIG. 2) between successive field sync elements **160** in the modulation frame. If used for equalizer training, the interval **220** is not short enough to enable receivers to accurately track temporal multipath variations quickly enough to yield effective reception. One possible approach is to explicitly introduce field sync elements **160** more frequently into the modulation frame. The required system modifications are illustrated in FIG. 10. Such an approach would be politically detrimental in that it would render existing ATSC DTV transmission and reception equipment obsolete. As such, the direct addition of supplemental training waveform components is economically unjustifiable.

[00042] An economically viable approach requires backward compatibility with existing receivers. Such an approach may be identified by the following comments:

1. Enables continuous reliable viewing in the presence of significant multipath channel impairments;

2. Significant multipath channel impairments to include ghosts generated by reflections and/or obstructions moving at 100 kilometers per hour (62 MPH) with respect to reception equipment;

3. This approach is done while every pre-existing legacy ATSC DTV receiver receives the same signal, and to the extent that it can be received in the absence of any transmission waveform modifications.

[00043] The present invention comprises a method of introducing new, more frequent training symbols into the modulation frame through backward compatible induction. FIG. 11 illustrates the necessary modifications to ATSC DTV transmission and reception systems. In this method, supplemental training sequence data **1110** is introduced into the service multiplexer **125** in the form of periodic packets. Such packets are formed with the ATSC DTV standard in mind and in such a manner as to induce frequent and advantageous training symbol components **1120** into the ATSC DTV modulation frame (as illustrated in FIG. 2).

[00044] The operation of the training symbol induction method is best described by example. In a first example, one training symbol packet is introduced into the service multiplexer **125** after every 12 conventional MPEG-2 service multiplex packets. The effective service rate is reduced by $1/13 \cong 8\%$ in the interest of inducing the advantageous frequent training symbol components.

[00045] FIG. 12 emphasizes the introduction of the training symbol packet data **1110** and the subsequent interleave processing **145,** inherent to the ATSC DTV standard transmission, which has the effect of distributing the induced training symbols throughout the modulation frame (as illustrated in FIG. 2).

[00046] FIG. 13 illustrates the sequence of new supplemental training symbol packets **1110** and conventional MPEG-2 multiplex packets **1310** at the output of the service multiplexer **125.** FIG. 14 illustrates the interleave process **145** in accordance with the ATSC DTV standard.

[00047] The distribution of MPEG-2 training symbol bytes by the interleaver **145** in the modulation frame (FIG. 2) is illustrated in FIG. 15 using an example where 1 training sequence packet is introduced per 5 conventional MPEG-2 data packets, or 6 total MPEG-2 packets. In this illustration, every box represents a byte of multiplexed data read left-to-right, then top-to-bottom. The numbered boxes indicate the positions of the post-interleave training symbol bytes in accordance with the ATSC DTV standard byte interleave process **145.** In this manner, each byte of each training sequence packet **1110** in the service multiplexer **125** is mapped through the interleave process **145.** Not shown is the addition of Reed-Solomon (R/S) check bytes **140** to each service multiplex packet in accordance with the ATSC DTV standard transmission practice.

[00048] Subsequent ATSC DTV standard processing is required before corresponding new supplemental training symbols **1120** are manifested into the DTV modulation frame (FIG. 2). The byte interleaved service multiplex, which is the output of the byte interleaver **145,** is applied to a TCM (trellis-coded modulation) byte interleaver as shown in FIG. 16. Each of the 12 parallel TCM encode processes **1650** involve bit interleaving as shown in FIG. 17 and TCM encoding as shown in FIG. 18. In the induction method disclosed, each induction data bit is mapped from the interleaved service multiplex data stream (output of byte interleaver **145**) to the modulation frame (per the ATSC standard as illustrated in FIG. 2) in the same manner that the induction data packet bytes were mapped through the R/S encode process and subsequent byte

interleave process into the interleaved service multiplex data stream (in the manner of FIG. 15).

[00049] The essence of this method is the exploitation of the mapping to induce frequent regular periodic training symbol components into the modulation frame so as to enable effective multipath reception at the compatible receiver while maintaining backwards-compatibility with pre-existing legacy reception equipment. It is important that the training symbol components induced into the ATSC DTV modulation frame be of sufficient number and frequency as to enable effective multipath reception. Such a frequency and number are determined by evaluating relevant propagation parameters.

[00050] The first relevant propagation parameter is the multipath delay spread. The relevant VHF and UHF multipath delay spreads are on the order of up to 100 μs. Another relevant propagation parameter is the highest transmission frequency. This frequency f_{max} corresponds to the highest terrestrial broadcast television channel:

$$f_{max} \cong 800\,\text{MHz}$$

The minimum transmission wavelength λ_{min} is computed from the highest transmission frequency f_{max} using:

$$\lambda_{\min} \cong \frac{c}{f_{\max}} \cong \frac{3\times10^8}{800\times10^6} \cong .375\,\mathrm{m}$$

The maximum multipath reflection component velocity $v_{\max}$ is calculated in terms of the maximum number of wavelengths per second from the 100 kph benchmark as follows:

$$v_{\max} \cong 2\times100\,\mathrm{kph} \cong 200\,\mathrm{kph} \cong 200\,\mathrm{kph}\times\frac{1000\,\mathrm{m}}{\mathrm{km}}\times\frac{1\,\mathrm{hr}}{3600\,\mathrm{s}}\times\frac{\lambda_{\min}}{.375\,\mathrm{m}} \cong 150\frac{\lambda_{\min}}{\mathrm{s}}$$

[00051] The corresponding minimum multipath-ray phase-change or phase-rotation periodicity $T_{reflection}$ is calculated from this $v_{\max}$ using:

$$T_{reflection} \cong \frac{1}{150} \cong \frac{7\,\mathrm{ms}}{\lambda_{\min}}$$

Finally, experience indicates the prudence of offering provisions for updating multipath equalizers more than 10 times per minimum path variation cycle interval. Using instead a more conservative factor of 20, the

recommended equalizer update interval is calculated to be

$$T_{update} \cong \frac{7\,\mathrm{ms}}{\lambda_{\min}} \times \frac{\lambda_{\min}}{20\,\mathrm{updates}}$$

$$< 350\,\mu s$$

or

$$T_{update} < 350\,\mu s$$

In summary, adequate ATSC DTV multipath equalization calls for equalization of delay spreads on the order of up to 100 µs at update intervals of less than 350 µs.

[00052] The preferred embodiment is derived from the following comments:

1. The need to introduce training waveforms at intervals of less than 350 µs so that associated receivers can successfully track multipath using reliable reference trained equalizers;

2. The need to supply sufficient training symbols in each such training waveform so as to ensure the ability of trained equalizers to sufficiently train at the intervals indicated;

3. The need to match training waveform periodicity with those of the pre-existing ATSC standard;

4. The need to keep the enhancement simple; and

5. The need to restrict the introduction of training symbols to a reasonably small percentage of

the system data throughput so as to preserve information capacity.

[00053] The preferred embodiment includes the introduction of 4 induction packets per 52 multiplex packets. Periodicity is essential so that the receiver is able to find the induced reference symbols. A periodicity of 52 multiplex packets is chosen because 52 multiplex packets divides evenly into the 624 multiplex packets which map into the ATSC DTV modulation frame and into the 12-branch TCM encode interleave process in accordance with the ATSC DTV standard ($52 \times 12 = 624$).

[00054] In the preferred embodiment, 4 induction packets per 52 service multiplex packets map into approximately 96 full training symbols per 3 modulation segments (232 μs) plus 96 partial training symbols. These second 96 partial training symbols are partial in the sense that their state cannot be fully controlled due to the two-bit delay **1820** inherent in the ATSC DTV standard TCM encoding process, as illustrated in FIG. 18. Their state may only be partially controlled in the sense that the bit which is not subject to convolutional coding delay is used to map the major component of the symbol state as opposed to the entire symbol state. The relevant correlation processing gain is approximated using

$$10\log(96\times 1.5) > 20\text{dB}$$

which offers greater than 20 dB processing gain to resolve the channel response.

[00055] As such, the preferred embodiment offers adequate and sufficiently frequent means to characterize multipath suitably for reliable ATSC DTV receiver channel characterization and demodulation, or to otherwise serve as a reference against which to train the corresponding equalizers.

[00056] Also important to the successful implementation of the training symbol induction method is the necessity to ensure compatibility of the induction packets with existing receivers. It is necessary that pre-existing legacy receivers reject such packets. This is accomplished through one or both of the following techniques:

1. The induction process verifies or causes training symbol induction packets to be invalid and uncorrectable R/S codewords (distance > 10 R/S characters to nearest valid codeword) so as to be discarded by the receiver; and

2. The induction process causes training symbol induction packets to be associated with an unused MPEG-2 program channel so as to be discarded by the receiver.

[00057] The data overhead associated with either of these processes does not cause an appreciable degradation to the > 20 dB processing gain associated with the preferred embodiment described above. Of significance to the method disclosed is the fact that induced training symbols do not typically appear contiguously in the modulation frame, but are instead typically interspersed between data symbols. The result is that a longer time base is used to formulate each channel multipath approximation.

[00058] The preferred embodiment at the receiver is to use a reference-trained equalizer such as the one illustrated in FIG. 8. Such an equalizer would exploit the sufficiently frequent training waveform and the a-priori knowledge of training symbol locations to find the training symbols and to train the equalizer against them. Measures to acquire and maintain symbol and modulation frame timing would be required.

[00059] An alternative reception method involves the following:

1. Use of a correlator to determine a sufficiently accurate approximation $\hat{h}(n,m)$ for the multipath channel response $\bar{h}(n,m)$ **540** at every training waveform interval; and

2. Use of an LMS, RLS or other relevant technique to approximate the necessary inverse-channel function $\overline{h^{-1}}(n,m)$ **610** required in the implementation of the required equalizer $\hat{\overline{h^{-1}}}(n,m)$ **610**.

[00060] In terms of the correlator, an objection may be raised in terms of anticipated complexity. However, a very computationally efficient correlator is constructed as follows:

1. ATSC DTV 8-VSB symbol states (-7, -5, -3, -1, 1, 3, 5 and 7) are offset in accordance with the ATSC DTV standard by a pilot of magnitude 1.25, but the effective symbol states become (-5.75, -3.75, -1.75, 0.25, 2.25, 4.25, 6.25 and 8.25);

2. A reasonable and acceptable approximation to these states are the states (-6, -4, -2, 0, 2, 4, 6 and 8);

3. Correlation of a $96 \times 2 = 192$ symbol sequence involves 192 multiplies per point, which is extremely computationally intensive. However, the required multiplies, subject to the approximation above, may instead be implemented in fixed-point arithmetic using successive bit-shifts and adds (i.e., multiplication by 4 is a 2-bit shift; multiplication by 6 is the sum of the results of a 1-bit shift and a 2-bit shift). The resulting implementation significantly reduces computations; and

4. A minor modification of the ATSC DTV standard includes a change in the pilot level from 1.25 to 1 renders the above approximation (step 2) exact.

[00061] The preferred reception method involves the use of the correlator as described above to acquire and maintain symbol and frame timing while using the reference-trained equalization process of FIG. 8 to suppress multipath-induced intersymbol interference.